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# Project Summary

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# Environmental Assessment of a Reciprocating Engine Retrofitted with Selective Catalytic Reduction



C. Castaldini and L. R. Waterland

**This report describes emission results obtained from field testing of a gas-fired lean-burn reciprocating internal combustion engine retrofitted with a selective catalytic reduction (SCR) system for $NO_x$ reduction. Two series of tests were performed: a comprehensive test program to characterize catalyst inlet and outlet exhaust gas composition at a catalyst $NO_x$ reduction performance target of greater than or equal to 80 percent; and a 15-day exhaust monitoring program to measure the catalyst performance under typical engine operating conditions.**

**Emission measurements during the comprehensive test program included continuous monitoring of flue gas emissions; source assessment sampling system (SASS) sampling of the exhaust gas with subsequent laboratory analysis of samples to give solid particulate emissions, total organics in two boiling point ranges, compound category information within these ranges, and specific quantitation of the semivolatile organic priority pollutants; VOST sampling for volatile organic emissions at the catalyst outlet; modified EPA Method 6 sampling systems for $NH_3$ and total cyanides; and exhaust gas grab samples for $N_2O$ analysis by gas chromatography. Emission measurements during the 15-day monitoring program were limited to continuous monitoring of exhaust gas species.**

**Comprehensive test results indicated that during the 1-day test the $NO_x$ reduction performance of the catalyst was maintained relatively constant at 81 percent. $NO_x$ emissions at the catalyst inlet ranged from 2,200 to 2,600 ppm, as measured at 11.2 percent $O_2$ (2,400 ppm average). At the catalyst outlet, $NO_x$ ranged from 330 to 560 ppm, also at about 11.2 percent $O_2$ (445 ppm average).**

**CO emissions averaged 245 ppm at the catalyst inlet and 225 ppm at the outlet. Hydrocarbon emission data were not available for the comprehensive tests; however, emission results obtained during the extended emission testing indicated emissions in the range of about 1,500 to 1,800 ppm at both the inlet and outlet. Total organic ($C_{6+}$) emissions were apparently reduced across the catalyst from 4.9 to 1.5 mg/dscm (20 to 6.2 mg/bhp-hr). Emissions of two polynuclear aromatic hydrocarbon (PAH) species, naphthalene and phenanthrene, and a nitrophenol were quantitated. Again, catalyst inlet levels were higher than outlet levels. Outlet PAH emissions were at or below 0.4 $\mu$g/dscm (about 1.6 $\mu$g/bhp-hr).**

**During the extended 15-day performance test, the $NO_x$ reduction performance was also maintained relatively constant at about 80 percent. Only occasionally and briefly did $NO_x$ reduction fall below 80 percent. These brief low catalyst performance periods were attributed to engine load surges and an occasional malfunction in the $NH_3$ injection flowrate.**

*This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in two separate volumes of the same title (see Project Report ordering information at back).*

## Introduction

In California, the South Coast Air Quality Management District (SCAQMD) continues to be in nonattainment of both federal and state $NO_2$ standards. Stationary reciprocating internal combustion engines (ICEs) are estimated to contribute about 14 percent of the $NO_x$ (about 59 Mg/day (65 tons/day)) from all stationary sources and 5.1 percent of total $NO_x$ emissions in the basin. In 1979, the California Air Resources Board (CARB) proposed a control strategy for ICEs that called for retrofit of these sources with nonselective and selective gas treatment catalysts (NSCR and SCR, respectively). The proposed SCAQMD rule 1110 called for demonstration of 90 percent $NO_x$ reduction or an emissions limit of 0.28 $\mu$g/J (0.75 g/bhp-hr) of heat output. Following this proposed rule, there has been a sustained R&D effort to demonstrate the capability of commercially available NSCR and SCR catalysts and identify problems in their application. In September 1984, a modified version of this rule was adopted by SCAQMD calling for 80 percent $NO_x$ reduction demonstration with subsequent 70 percent reduction from existing lean-burn engines. The retrofit schedule calls for 80 percent of all existing lean-burn engines with capacity greater than 500 hp in the South Coast Air Basin to be controlled by December 31, 1987. The remaining lean-burn engines (all above 50 hp) are to be controlled by December 31, 1994.

This report describes the results of comprehensive emission tests and 15-day extended monitoring tests of a lean-burn reciprocating engine retrofitted with an SCR system. Emissions were measured at both the inlet and outlet of the catalyst to quantitate both $NO_x$ reduction performance and the impact of the catalyst on other pollutants.

The tests were performed on an Ingersoll-Rand 412 KVS (2,000-hp) four-stroke, turbocharged gas compressor engine owned and operated by Southern California Gas Company (SoCal). In April 1984, the engine was retrofitted with an Englehard SCR catalyst system. A similar system was previously tested on a slipstream of the engine and found capable of 90 percent $NO_x$ reduction. The catalyst, based on a proprietary metal oxide formulation, has an upper temperature limit of 427 °C (800 °F). The slipstream tests by SoCal had shown that 90 percent $NO_x$ reduction was achieved using an $NH_3$/NO injection rate of 1.0 (molar ratio) and an exhaust temperature of about 400 °C (750 °F).

## Summary and Conclusions

### *Engine Operation*

The test program called for the evaluation of $NO_x$ reduction performance of the catalyst and its effect on organic and inorganic gaseous pollutants during 1 day of comprehensive tests with the engine $NH_3$ injection rate adjusted for $NO_x$ reduction of greater than 80 percent at constant power output. In addition, the test program called for a continuous 15-day emission monitoring program to evaluate the $NO_x$ control capability with the engine operating under typical conditions with varying load and $NH_3$ injection rate.

Table 1 summarizes engine operating characteristics during the comprehensive tests. Engine load was maintained relatively constant, at about 1,270 kW (1,700 hp), throughout this portion of the test program. Brake-specific fuel consumption was 9.4 MJ/kWh (6,600 Btu/bhp-hr) based on fuel lower heating value. This is at the low end of representative four-stroke turbocharged engines. The $NH_3$ injection rate ranged from about 4.4 to 4.9 l/s (565 to 620 scfh), representing an $NH_3$/NO molar ratio of about 1.0. The $NH_3$ injection rate was controlled by a feedback system which monitored $NO_x$ at the engine outlet and set $NH_3$ injection rate to maintain a target $NO_x$ reduction of 80 percent.

Note that, prior to the test period, problems were experienced with the $NH_3$ control system, specifically the $NO_x$ analyzer and the $NH_3$ control valve.

### *Emission Measurements and Results — Comprehensive Tests*

The sampling and analysis procedures used in this test conformed to a modified EPA Level 1 protocol. The exhaust gas measurements included the following at both the catalyst inlet and outlet:

- Continuous monitoring for $O_2$, $CO_2$, CO, NO/$NO_x$, $NH_3$, and TUHC.
- SASS sampling.
- VOST sampling for volatile organics.
- Modified EPA Method 6 train sampling for $NH_3$ and total cyanide.
- Gas grab sample for $N_2O$ determination.

The analysis protocol included:

- Analyzing SASS train samples for

*Table 1. Engine Operation — Comprehensive Tests*

| *Parameter* | *Range* | *Average* |
|---|---|---|
| *Ambient* | | |
| *Dry bulb temperature, °C (°F)* | *22 to 33 (72 to 92)* | *29 (84)* |
| *Wet bulb temperature, °C (°F)* | *19 to 21 (67 to 72)* | *20 (68)* |
| *Relative humidity, percent* | *45 to 55* | *50* |
| *Barometric pressure, kPa (in. Hg)* | — | *96.2 (28.5)* |
| *Engine Operation* | | |
| *Engine load, $kW_t$ (bhp)[a]* | — | *1270 (1700)* |
| *Fuel flow, $m^3$/h (scfh)* | — | *327 (11,550)* |
| *Heat input, MW (million Btu/hr)[b]* | — | *3.29 (11.2)* |
| *Specific fuel consumption, kJ/kWh (Btu/bhp-hr)[b]* | — | *9390 (6610)* |
| *Air manifold pressure, kPa (psig)* | *25 to 28 (3.6 to 4.0)* | *26.5 (3.85)* |
| *Air manifold temperature, °C (°F)* | *68 to 70 (154 to 158)* | *69 (156)* |
| *Engine speed, rpm* | *320 to 333* | *325* |
| *Exhaust manifold temperature, °C (°F)* | *380 to 382 (716 to 720)* | *380 (718)* |
| *Catalyst/$NH_3$ System* | | |
| *Catalyst inlet temperature, °C (°F)* | *390 to 400 (740 to 750)* | *396 (745)* |
| *Catalyst outlet temperature, °C (°F)* | *344 to 382 (652 to 720)* | *362 (683)* |
| *$NH_3$ flowrate, l/s (scfh)* | *4.44 to 4.88 (565 to 620)* | *4.64 (590)* |
| *Gas Compressor* | | |
| *Suction pressure, MPa (psig)* | — | *4.02 (583)* |
| *Interstage pressure, MPa (psig)* | — | *7.86 (1,140)* |
| *Discharge pressure, MPa (psig)* | — | *18.87 (2,898)* |
| *Suction temperature, °C (°F)* | *26 to 35 (78 to 95)* | *29 (85)* |
| *Interstage temperature, °C (°F)* | *88 to 93 (180 to 200)* | *91 (195)* |
| *Discharge temperature, °C (°F)* | *107 to 118 (225 to 245)* | *113 (235)* |

[a] *Engine load obtained from engine performance curves.*
[b] *Heat input based on low heating value (LHV) of natural gas. Specific fuel consumption based on LHV of fuel.*

total organic content in two boiling point ranges: 100 to 300 °C by total chromatographable organics (TCO) analysis, and greater than 300 °C by gravimetry (GRAV).

- Analyzing the SASS train sorbent module extract for 58 semivolatile organic species including many of the PAH compounds.
- Performing infrared (IR) spectrometry analysis of organic sample extracts.
- Analyzing VOST traps for 34 volatile organic priority pollutant species.

Table 2 summarizes emissions measured at the engine muffler outlet (catalyst inlet) and the catalyst outlet. Continuous monitored emissions ($O_2$, $CO_2$, CO, NO/$NO_x$, and TUHC) were measured upstream of the $NH_3$ injection, located upstream at the engine muffler. Emissions are presented in milligrams per dry standard cubic meter, nanograms per Joule heat input, and milligrams per brake horsepower-hour shaft output.

As shown in Table 2, $NO_x$ emissions were reduced 81 percent on the average, from 2,760 to 513 ng/J (19.2 to 3.57 g/bhp-hr). Actually, $NO_x$ reductions did not vary significantly from this average throughout the test, indicating a relatively constant $NO_x$ reduction performance of the catalytic system.

$NH_3$ emissions measured at the catalyst outlet with an extractive sampling system averaged 39 ng/J (0.27 g/bhp-hr), corresponding to a volumetric gas concentration of 93 ppm. $NH_3$ emissions, also measured at this location by a continuous monitoring system, confirmed these results. Total cyanide increased significantly across the catalyst to a concentration of 2.4 mg/dscm at the catalyst outlet. Both TCO and GRAV organics were apparently reduced by the catalyst by about 46 and 82 percent, respectively. This performance coincides with relatively low CO levels that were also measured at the catalyst outlet. Solid particulate emissions were not detectable within the accuracy of the analytical procedure.

Table 3 summarizes the emissions of volatile and semivolatile organic compounds detected by GC/MS analyses of VOST traps and SASS sorbent extract samples. Volatile organics were measured only at the catalyst outlet. These data show benzene and toluene as the principal compounds with concentrations of about 900 and 250 µg/dscm, respectively, at the catalyst outlet. Other volatiles detected were xylenes, chlorobenzenes, and ethylbenzenes with concentrations below 100 µg/dscm. Naphthalene and 2-nitrophenol were the major semivolatile organics detected at the catalyst inlet. Their concentrations of 8.4 and 5.3 µg/dscm, respectively, were reduced at the outlet to undetectable levels ($\leq$0.4 µg/dscm).

## Emission Measurements and Results — 15-Day Monitoring

The sampling and analysis protocol for this portion of the test program consisted of continuous monitoring of inlet and outlet exhaust gas for $O_2$, $CO_2$, CO, NO/$NO_x$, $NH_3$, and TUHC with certification of $NO_x$ analyzer readings using EPA Method 7. Since both engine power output and $NH_3$ injection rate were not restricted to specified ranges, the data obtained can be considered reflective of typical operating practice. Figures 1 through 6 summarize emission results. Each data point in these figures represents an hourly average. The data indicate relatively steady engine operation with exhaust $O_2$ levels at about 11 percent and $CO_2$ at about 5.5 percent. $NO_x$ emissions ranged between 1,200 and 1,600 ppm corrected to 15 percent $O_2$ at the inlet and about 100 to 400 ppm at 15 percent $O_2$ at the catalyst outlet. $NO_x$ reduction efficiency translates to nearly constant 80 percent as shown in Figure 3. The two data points indicating reduced or no $NO_x$ reduction were generally caused by an occasional loss of $NH_3$ flow or a surge in engine load. These

*Table 2. Summary of Exhaust Gas Emissions*

| | Catalyst inlet[a] | | | Catalyst outlet[a] | | |
|---|---|---|---|---|---|---|
| Specie | mg/dscm | ng/J | mg/bhp-hr | mg/dscm | ng/J | mg/bhp-hr |
| $NO_x$ (as $NO_2$) | 4,630 | 2,760 | 19,200 | 860 | 513 | 3,570 |
| CO | 287 | 171 | 1,190 | 265 | 158 | 1,100 |
| $NH_3$[b] | | | | 65 | 39 | 270 |
| Total cyanide (as CN) | 0.007 | 0.004 | 0.03 | 2.4 | 1.4 | 10 |
| $N_2O$[c] | 180 | 108 | 750 | 79 | 47 | 327 |
| Total chromatographable organics ($C_7$ to $C_{16}$) | 1.7 | 1.0 | 7.0 | 0.9 | 0.54 | 3.7 |
| Total GRAV organics ($C_{16+}$) | 3.2 | 1.9 | 13 | 0.6 | 0.34 | 2.4 |

[a]Average exhaust gas $O_2$ and $CO_2$ were 11.2 and 5.5 percent, respectively, at both catalyst inlet and outlet.
[b]$NH_3$ emissions at the engine outlet were not measured by wet chemical analysis.
[c]$N_2O$ emissions were measured after the comprehensive test period. Catalyst inlet and outlet $NO_x$ during these tests were similar to levels measured during the comprehensive tests.

*Table 3. Volatile and Semivolatile Organic Emissions*

| Compound | Catalyst Inlet (µg/dscm) | Catalyst Outlet (µg/dscm) |
|---|---|---|
| Volatile organics:[a] | | |
| Benzene | NA[b] | 915 |
| Chlorobenzene | | 61 |
| Chloroethane | | 1.8 |
| 1,1,dichloroethane | | 1.5 |
| Ethylbenzene | | 20 |
| Tetrachloroethane | | 2.4 |
| Toluene | | 247 |
| Acetone | | 17 |
| Total xylenes | | 85 |
| Semivolatile organics: | | |
| Naphthalene | 8.4 | 0.4 |
| Phenanthrene | 0.4 | <0.4 |
| 2-Nitrophenol | 5.3 | <0.4 |
| Di-n-butyl phthalate[c] | 3.1 | 5.5 |
| Bis(2-ethylhexyl)phthalate[c] | 1.9 | 1.0 |

[a]Volatile organic emissions measured only at the catalyst outlet. Values presented are blank corrected average of two measurements.
[b]NA = Not available. No measurements for volatile organics performed at the catalyst inlet.
[c]Suspected contaminants, commonly found in laboratory blanks.

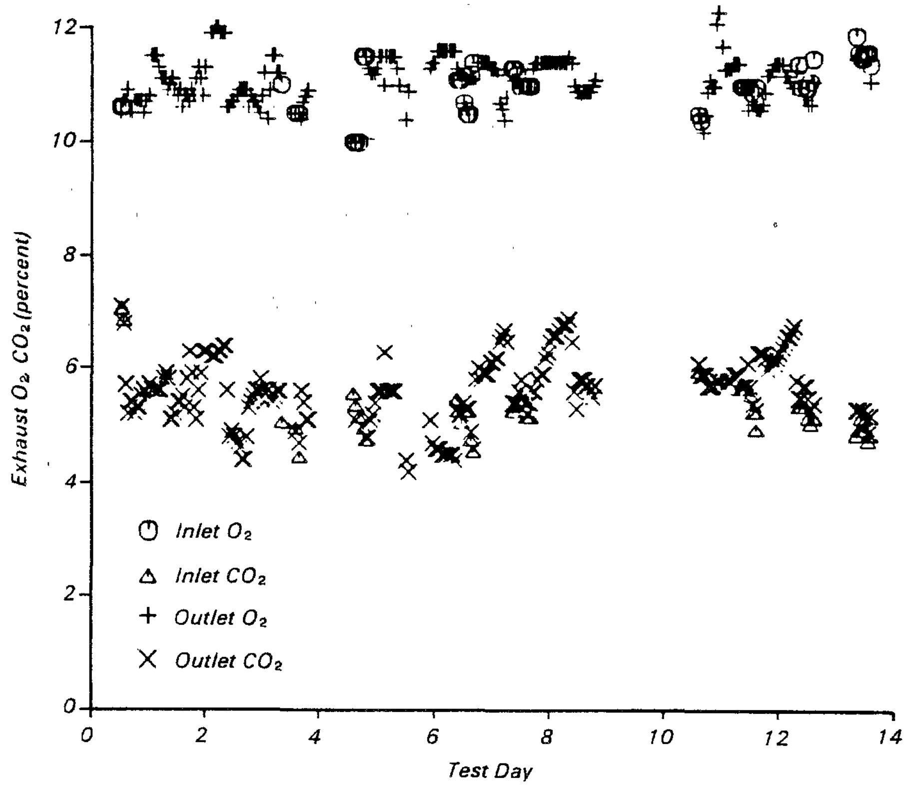


***Figure 1.*** *Exhaust $O_2$ and $CO_2$ for the extended continuous monitoring period.*

episodes were infrequent and generally brief. Periods of no data are indicative of engine shutdown due to a lubricating system problem. $NH_3$ emissions at the catalyst outlet, Figure 4, ranged typically between zero and 150 ppm. These data were collected by using two $NO_x$ analyzers, one equipped with a molybdenum and one with a stainless steel converter, respectively. $NH_3$ was determined by the difference between the $NO+NO_2+NH_3$ and $NO+NO_2$ readouts of the two online instruments. Combustible emissions were 100 to 300 ppm for CO and 750 to 1,250 ppm for TUHC.

## Summary

Emission test of a lean-burn reciprocating internal combustion engine retrofitted with a SCR $NO_x$ control system suggest that $NO_x$ emission reduction of 80 percent can be maintained with good control on $NH_3$ injection rate at relatively constant engine load. The catalyst was found to slightly reduce CO emissions including detected organic compounds. $NH_3$ breakthrough emissions ranged generally between zero and 150 ppm corrected to 15 percent $O_2$. Measurements by wet chemical methods support these levels. Total cyanides increased by 3 orders of magnitude across the catalyst to a level of 1.4 ng/J at the catalyst outlet.

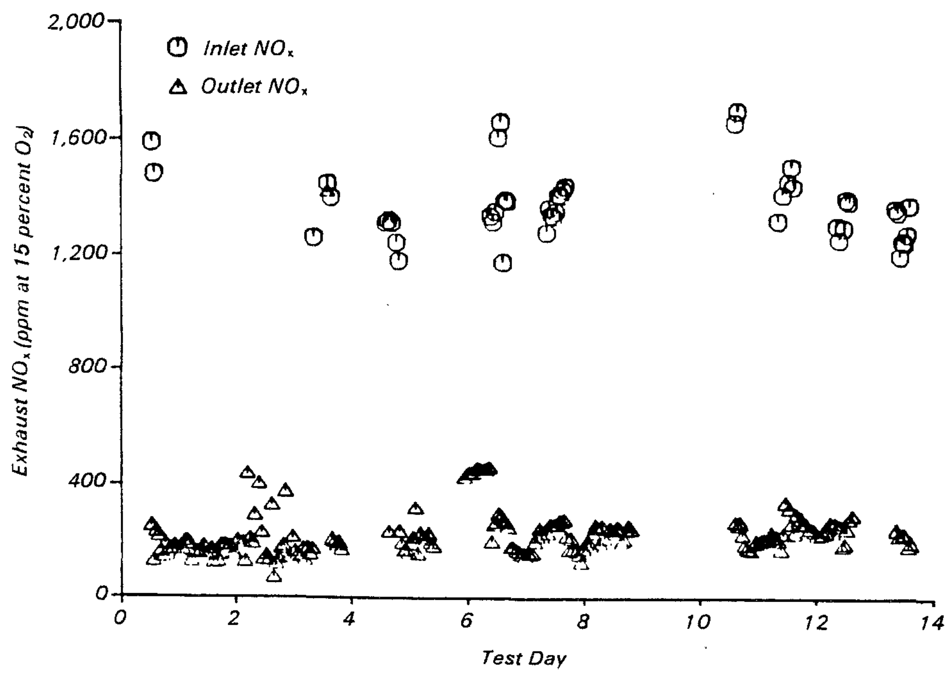


***Figure 2.*** *Exhaust $NO_x$ levels for the extended continuous monitoring period.*



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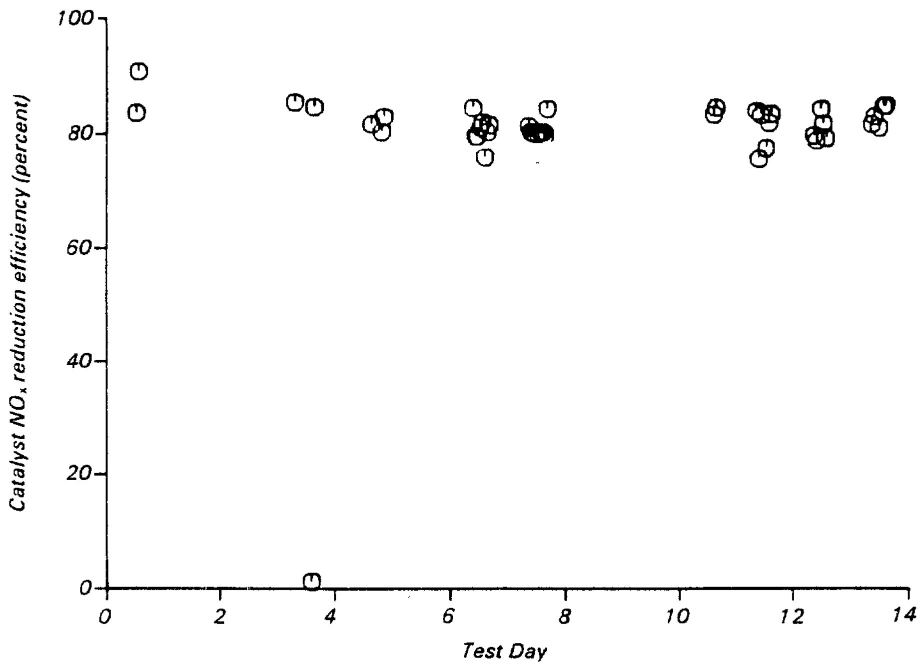


*Figure 3.* Catalyst $NO_x$ reduction efficiency for the extended monitoring period.

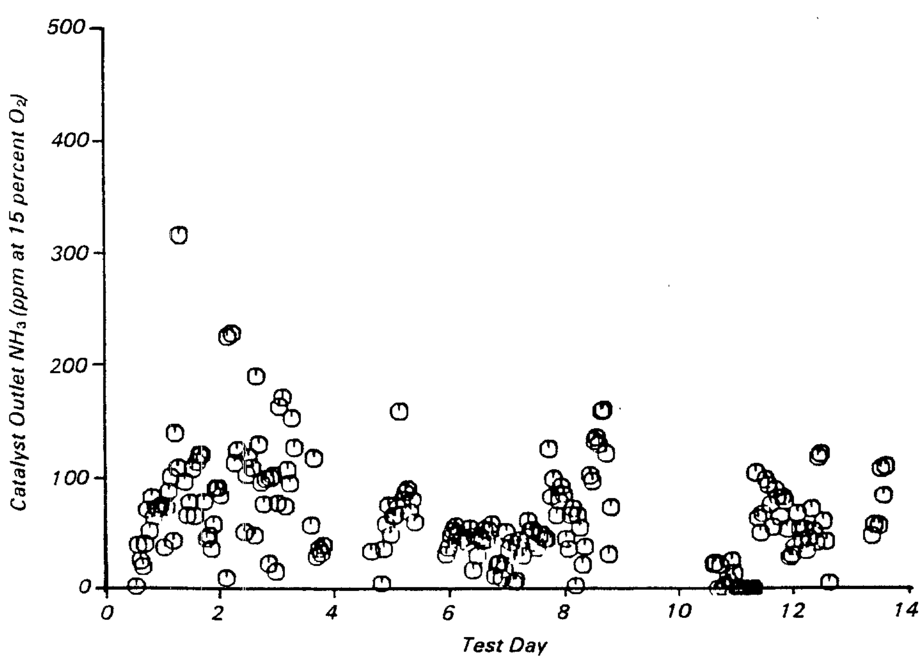


*Figure 4.* Catalyst outlet $NH_3$ emissions for the extended continuous monitoring period.

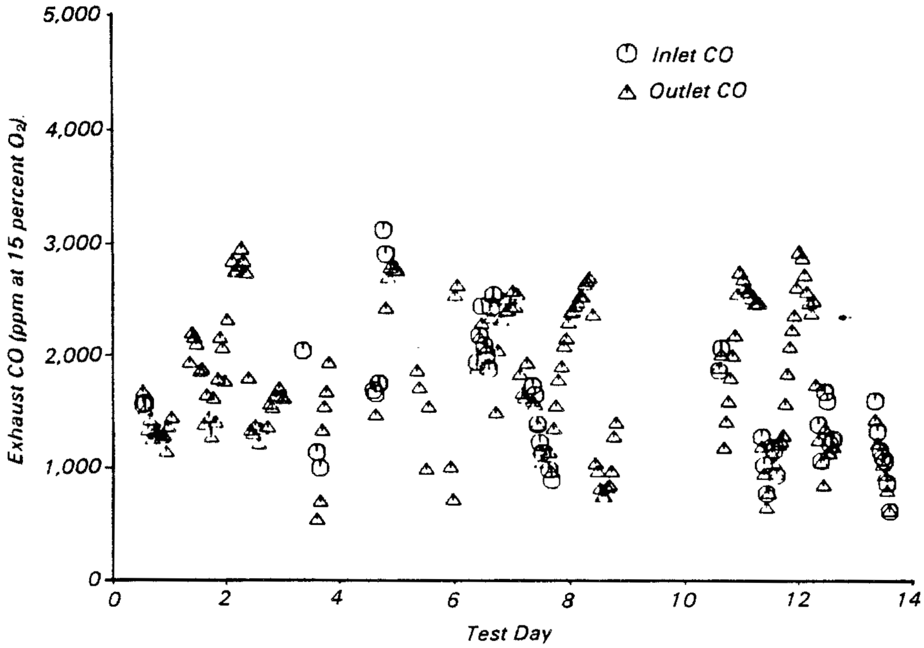


*Figure 5.* *Exhaust CO levels for the extended continuous monitoring period.*

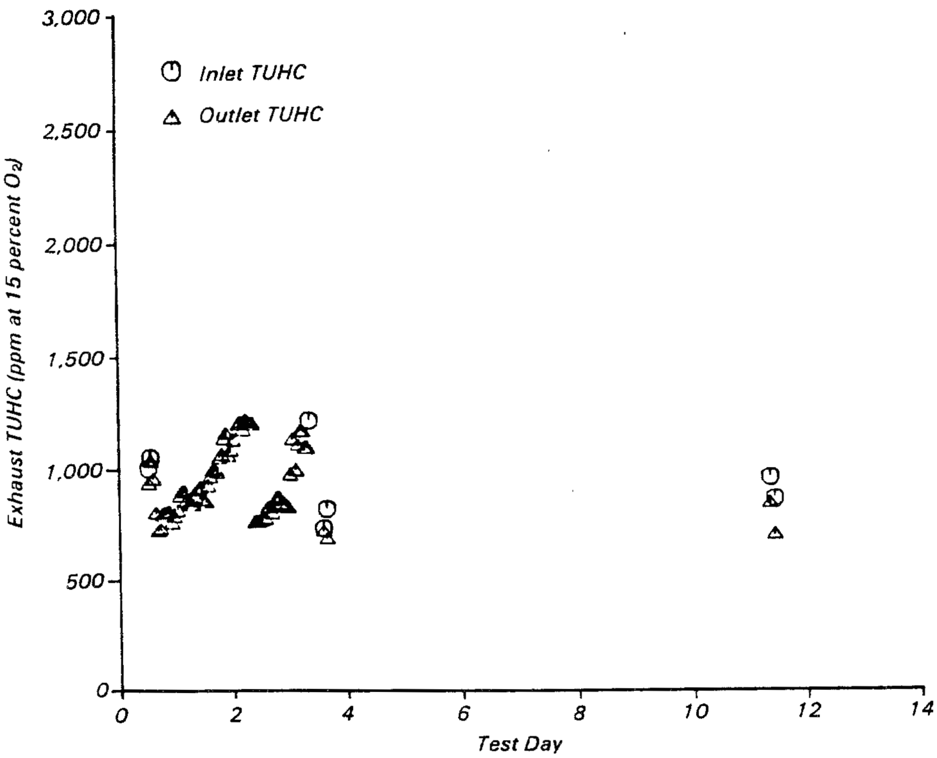


*Figure 6.* *Exhaust hydrocarbon levels for the extended continuous monitoring period.*



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*C. Castaldini and L. Waterland are with Acurex Corp., Mountain View, CA 94039.*
***Joseph A. McSorley** is the EPA Project Officer (see below).*
*The complete report consists of two volumes, entitled "Environmental Assessment of a Reciprocating Flame Retrofitted with Selective Catalytic Reduction:"*
*"Volume I. Technical Results," (Order No. PB 86-183 779/AS; Cost: $11.95)*
*"Volume II. Data Supplement," (Order No. PB 86-183 787/AS; Cost: $11.95)*
*The above documents will be available only from: (cost subject to change)*
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# Project Summary

# Environmental Assessment of $NO_x$ Control on a Spark-Ignited, Large-Bore, Reciprocating Internal-Combustion Engine

C. Castaldini

**This two-volume report gives emission results for a spark-ignited, large-bore, reciprocating, internal-combustion engine operating both under baseline (normal) conditions, and with combustion modification controls to reduce $NO_x$ emissions to levels below the proposed new source performance standard (NSPS) for such engines. Exhaust gas measurements (in addition to continuous monitoring of criteria gas emissions) included total organics in two boiling point ranges, compound category information within these ranges, specific quantitation of the semivolatile organic priority pollutants (POMs), flue gas concentrations of 73 trace elements, and particulate matter. Exhaust $NO_x$ emissions were reduced almost 50 percent, from a baseline level of 1,260 ng/J to 654 ng/J (730 to 420 ppm, corrected to 15 percent $O_2$ dry) by increasing the operating air/fuel ratio of the engine. Accompanying this reduction was a slight increase in engine efficiency. CO, methane, total hydrocarbon, and total semivolatile organic compound emissions were increased from 10 to 65 percent under low-$NO_x$ operation. However, total nonvolatile organic emissions decreased 55 percent. The organic emissions for both tests consisted primarily of aliphatic hydrocarbons with some carboxylic acids, phenols, and low-molecular-weight fused-ring aromatics. POMs were detected in concentrations below 4 $\mu$g/dscm.**

***This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in two separate volumes of the same title (see Project Report ordering information at back).***

## Introduction

This report describes emission results obtained from field tests of the exhaust gas from a spark-ignited, large-bore, reciprocating, internal-combustion engine. Objectives of the tests were to measure exhaust gas emissions and evaluate the operating efficiency of the engine, both under baseline (normal) operating conditions, and with combustion modification controls to reduce $NO_x$ emissions to levels below the proposed new source performance standards (NSPS) for such engines. Emission measurements included continuous monitoring of exhaust gas emissions; source assessment sampling system (SASS) sampling of the exhaust gas with subsequent laboratory analysis of samples to give total flue gas organics in two boiling point ranges, compound category information within these ranges, specific quantitation of the semivolatile organic priority pollutants, and flue gas concentrations of 73 trace elements; and Method 5 sampling for particulate.

Exhaust $NO_x$ emissions were reduced almost 50 percent, from a baseline level of 1,260 ng/J to 654 ng/J by increasing the operating air/fuel ratio of the engine. Accompanying this reduction was a slight increase in engine efficiency. CO, methane, total hydrocarbon, and total semivolatile organic compound emissions were increased from 10 to 65 percent under low-$NO_x$ operation. However, total nonvolatile organic emissions decreased 55 percent. Emissions of anthracene/phenanthrene and chrysene/benz(a)anthracene were 3 to 4 $\mu g$/dscm for both tests; levels of other POMs were less than detectable (2 $\mu g$/dscm). The organic emissions for both tests consisted primarily of aliphatic hydrocarbons with some carboxylic acids, phenols, and low-molecular-weight fused-ring aromatics.

## Summary and Conclusions

### Test Engine

The test engine was a large-bore, turbocharged, 1,120-kW (1,500-Bhp) two-stroke, opposed-piston spark-ignited Model 37TDSB-1/8 engine manufactured by the Fairbanks Morse Engine Division of Colt Industries. Figure 1, a schematic of the engine, shows the turboblower arrangement for the inlet combustion air and the opposed piston design. The combustion air is drawn into the turbocharger, where it is compressed and discharged through an air cooler to the positive-displacement lobe-type blower. The blower, driven by the upper engine crankshaft, discharges the air directly to the cylinders through the engine intake manifold. The air/fuel mixture is compressed between the two pistons which work vertically toward each other in each cylinder. The upper and lower pistons drive separate crankshafts interconnected by a vertical drive. Hot exhaust gas from the lower cylinder ports drives the turbine of the turbocharger assembly. The fuel is ignited by spark ignition cells, arranged two per cylinder.

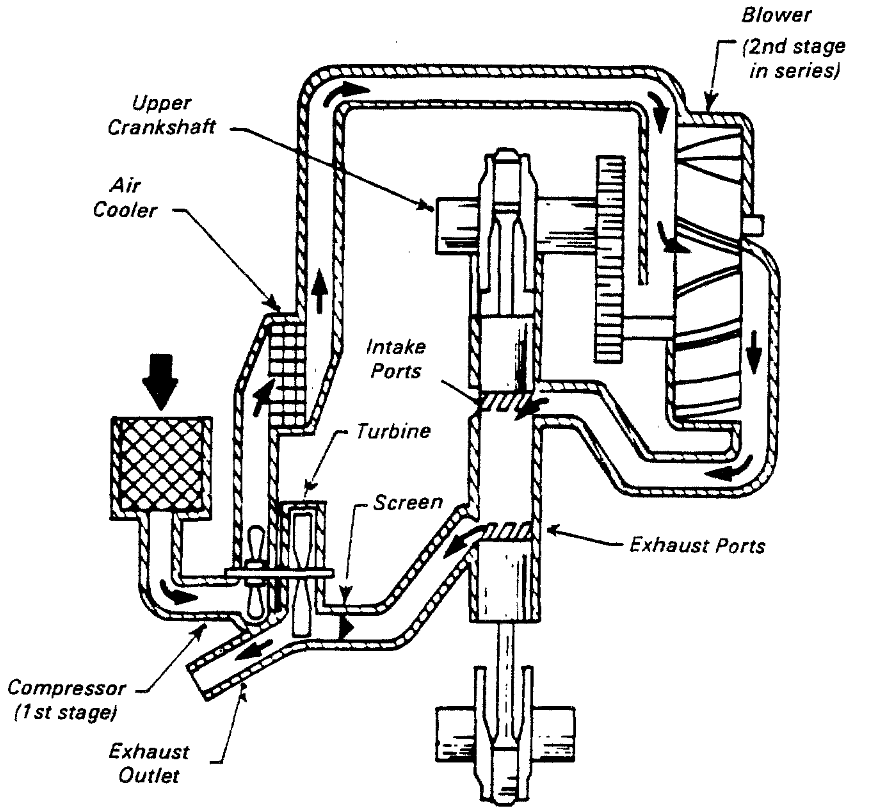


*Figure 1.* *Schematic of turboblower arrangement (courtesy of the Fairbanks Morse Division of Colt Industries).*

### Engine Operation and Test Arrangements

The test program called for the analysis of flue gas samples collected during normal operation (baseline conditions) and with combustion modifications applied to lower $NO_x$ emisisons. Table 1 summarizes the engine specifications and operating parameters during both the baseline and low-$NO_x$ tests.

Since this engine design is usually marketed without the turbocharger and manifold air cooler existing on the test engine, it was necessary to reduce the effect of turbocharging during the baseline test. To reduce the effect of turbocharging, a portion of the combustion air was bypassed around the manifold air cooler. The resulting increase in combustion air temperature lowered the air mass flowrate, giving an air/fuel ratio which is more representative of the blower-scavenged design. The percent bypass air during the baseline tests was 16.4 percent, determined by the air flow control limits available on this test engine. Thus, baseline operation was as representative of normal blower-scavenged engine operation as could be achieved with the turbocharger in place.

The low-$NO_x$ operation consisted of increasing the air/fuel ratio by eliminating the manifold air cooler bypass used during the baseline test and increasing the efficiency of the inlet manifold cooler. This modification reduced the inlet air temperature as well as increasing the air/fuel ratio. Engine power output was maintained nearly constant by decreasing fuel flow, while efficiency increased by about 0.4 percent during the low-$NO_x$ test.

### Emission Measurements and Results

The sampling and analysis procedures used in this test program conformed to a modified EPA Level 1 protocol. Except for continuous monitoring of exhaust gas emissions, all exhaust gas was measured at the engine muffler exit into the uninsulated exhaust stack. Emissions measurements included:

- Continuous monitoring for $NO_x$, NO, CO, $CO_2$, $O_2$, TUHC, and $CH_4$
- Source assessment sampling system (SASS) for trace element and organic emissions
- EPA Method 5 sampling for solid and condensable particulate mass emissions
- Grab sampling for onsite analysis of $C_1$ to $C_6$ hydrocarbons by gas chromatography
- Bosch smoke pot

In addition, samples of the engine lube oil were collected for analysis.

- Analyzing the lube oil and SASS train samples for 73 trace elements using spark source mass spectrometry (SSMS), supplemented by atomic absorption spectrometry (AAS)



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*Table 1. Spark Engine Design and Operating Parameters*

| *Design Parameters (Engine Specifications)* | | |
|---|---|---|
| *Model designation* | *38TDS8-1/8* | |
| *Configuration* | *2 stroke, O.P.* | |
| *Bore, m (in.)* | *0.206 (8-1/8)* | |
| *Stroke, m (in.)* | *0.254 (10) x 2* | |
| *No. of cylinders* | *6* | |
| *Displacement/cylinder $m^3$ ($in.^3$)* | *0.017 (1037)* | |
| *Compression ratio* | *9.7:1* | |
| *BMEP, kPa (psi)* | *731 (106)* | |
| *Power/cylinder at rpm, $kW_t$ (Bhp)* | *186 (250) at 900* | |
| *Spark timing* | *4.5° before minimum volume (BMV)* | |
| *Lubricating oil* | *Pegasus 485* | |
| *Hours since overhaul* | *1050* | |
| *Operating Parameters* | *Baseline* | *$NO_x$ Control Test* |
| *RPM (percent rating)* | *900 (100%)* | *900 (100%)* |
| *$kW_t$ (Bhp) (percent rating)* | *1,117 (1,498) (99.8%)* | *1,123 (1,505) (100%)* |
| *$kW_e$ (percent rating)* | *1,085 (97.8%)* | *1,091 (98.9%)* |
| *BMEP, kPa (psi)* | *731 (106)* | *731 (106)* |
| *Fuel flow, $m^3$/hr ($ft^3$/hr)* | *354 (12,492)* | *352 (12,426)* |
| *BSFC, g/kW-hr (lb/Bhp-hr)* | *217 (0.356)* | *215 (0.353)* |
| *Fuel rate, kW fuel/kW out (Btu/Bhp-hr)* | *2.91 (7413)* | *2.88 (7340)* |
| *Ignition timing* | *4.5° BMV* | *4.5° BMV* |
| *Compressor inlet air temp., K (°F)* | *302 (85)* | *302 (85)* |
| *Compressor outlet air temp., K (°F)* | *356 (181)* | *359 (187)* |
| *Manifold air cooling bypass, percent* | *16.4* | *0* |
| *Blower suction air temp., K (°F)* | *331 (136)* | *316 (110)* |
| *Blower discharger air temp., K (°F)* | *345 (161)* | *337 (146)* |
| *Blower discharge pressure, kPa (psig)* | *60 (8.7)* | *71 (10.3)* |
| *Air flow, kg/s (lb/min)* | *2.56 (338.3)* | *2.90 (383.4)* |
| *Fuel-air ratio* | *0.0271* | *0.0240* |
| *Combined cylinder exhaust temp., K (°F)* | *732 (858)* | *699 (799)* |
| *Turbine exhaust temp., K (°F)* | *652 (715)* | *617 (652)* |
| *Lube oil consumption, ml/s (gph)* | *0.45 (0.43)* | *0.45 (0.43)* |
| *Engine efficiency, percent* | *34.3* | *34.7* |
| *Average Ambient Atmospheric Conditions* | | |
| *Outdoor temp. dry bulb, K (°F)* | *281 (46)* | *284 (51)* |
| *Barometric pressure, kPa (in. Hg)* | *98.2 (29.08)* | *98.6 (29.20)* |
| *Humidity, percent* | *60* | *62* |

- Analyzing SASS train samples for total organic content in two boiling point ranges: 100 to 300°C by total chromatographable organics (TCO) analysis and >300°C by gravimetry (GRAV)
- Analyzing the SASS train sorbent module extract for 58 semivolatile organic species including many POM compounds
- Performing infrared (IR) spectrometry analysis of organic sample extracts
- Performing liquid chromatography (LC) separation of selected sample extracts with subsequent TCO, GRAV, and IR analyses of LC fractions
- Performing direct insertion probe and batch inlet low resolution mass spectrometry (LRMS) of selected sample extracts

Bioassay tests were also performed on the exhaust sample SASS organic sorbent module extract to estimate this sample's potential toxicity and mutagenicity.

Table 2 summarizes exhaust gas emissions measured in the test program. Emissions are presented in both ng/J heat input and as mg/dscm of exhaust gas.

As noted in Table 2, $NO_x$ emissions were decreased under low-$NO_x$ operation to 654 ng/J from a baseline of 1,260 ng/J. This decrease in $NO_x$ emissions was accompanied by increases in all relatively volatile combustible emissions, CO, TUHC, $CH_4$, and total semivolatile organics, although nonvolatile organic emissions decreased. Emission levels of the inorganic elements noted in Table 2 were relatively unchanged in going to low-$NO_x$ operation from the baseline condition.

As a measure of the potential significance of emission levels for further monitoring and evaluation, Table 2 also lists occupational exposure guidelines for most pollutants in the table. The guidelines listed are generally either the time-weighted-average Threshold Limit Values (TLV) established by the American Conference of Governmental Industrial Hygienists, or the 8-hour time-weighted-average exposure limits estabalished by the Occupational Safety and Health Administration. These are noted only to aid in ranking emissions for further evaluation. In this respect, species emitted at levels several orders of magnitude higher than their guideline might warrant further consideration. Species emitted at levels significantly lower than their occupational exposure guideline might be considered of lesser concern. Only elements emitted at levels exceeding 10 percent of their guideline are noted in Table 2.

Table 2 shows that the only pollutants emitted at levels which exceeded their respective guidelines were $NO_x$, CO, and Cu in the baseline test and $NO_x$, CO, Cu, Fe, and Cr in the low-$NO_x$ test. The trace elements were emitted at levels at most a few times higher than their guidelines. In contrast, the criteria pollutants CO and $NO_x$ were present in the exhaust at levels of almost one (CO) to well over two ($NO_x$) orders of magnitude higher than their guidelines. This suggests that $NO_x$ emissions achieved may be the most significant change.

Analyses of SASS train samples for POM and other organic compounds (the semivolatile organic priority pollutant species) were performed. Only anthracene/phenanthrene and chrysene/benz(a)anthracene isomers were detected at levels above 2 µg/dscm. These were present at 3 to 4 µg/dscm levels for both tests.

SASS train organic extract samples were subjected to LC fractionation with TCO, GRAV, IR, and LRMS analysis of LC fractions in attempts to elucidate the chemical character of the exhaust gas organic material. These analyses sug-

**Table 2.** *Summary of Flue Gas Emissions*[a]

| Compound | Baseline Test: Per Heat Input (ng/J) | Baseline Test: Average Concentration (mg/dscm) | Low-$NO_x$ Test: Per Heat Input (ng/J) | Low-$NO_x$ Test: Average Concentration (mg/dscm) | Occupational Exposure Guideline[b] (mg/dscm) |
|---|---|---|---|---|---|
| *Criteria Pollutant and Other Vapor Species* | | | | | |
| $NO_x$ (as $NO_2$) | 1,260 | 1,900 | 654 | 976 | 6.0 |
| CO | 120 | 198 | 198 | 295 | 55 |
| $CH_4$ | 293 | 480 | 323 | 482 | |
| TUHC (as $C_3H_8$) | 960 | 1,600 | 1,100 | 1,640 | |
| Solid particulate | 12.5 | 20 | 16.2 | 24.2 | 10.0[c] |
| Condensable particulate | 7.3 | 12 | 7.5 | 11.2 | |
| Total chromatographabale organics ($C_1$-$C_{16}$) | 1.3 | 2.1 | 1.6 | 2.4 | |
| Total nonvolatile organics (>$C_{16}$) | 35 | 57.8 | 15 | 22.1 | |
| *Trace Elements* | | | | | |
| Copper, Cu | 0.15 | 0.25 | 0.18 | 0.27 | 0.10[d] |
| Iron, Fe | — | —[e] | 1.1 | 1.6 | 1.0 |
| Chromium, Cr | 0.013 | 0.022 | 0.053 | 0.079 | 0.050 |
| Phosphorus, P | 0.0067 | 0.011 | 0.060 | 0.090 | 0.10 |
| Silver, Ag | 0.0010 | 0.0017 | 0.0046 | 0.0068 | 0.010 |
| Potassium, K | >0.48 | >0.80 | >0.66 | 0.98 | 2.0[f] |
| Sodium, Na | >0.48 | >0.80 | >0.54 | 0.80 | 2.0[f] |
| Lead, Pb | 0.012 | 0.020 | 0.0074 | 0.011 | 0.050[d] |
| Calcium, Ca | 0.35 | 0.59 | 0.18 | 0.27 | 2.0 |
| Selenium, Se | 0.035 | 0.059 | 0.023 | 0.034 | 0.20 |
| Cobalt, Co | — | — | 0.018 | 0.027 | 0.10 |
| Nickel, Ni | 0.0014 | 0.023 | 0.0013 | 0.0019 | 0.10 |

[a]Exhaust $O_2$ and $CO_2$ levels were 12.1 and 4.9 percent, respectively, for the baseline test and 13.2 and 4.4 percent, respectively, for the low-$NO_x$ test.
[b]Time-weighted-average, TLV, unless noted.
[c]For nuisance particulate.
[d]8-Hr time-weighted-average OSHA exposure limit.
[e]Dashes indicate the pollutant was not quantifiable.
[f]Ceiling limit.

gested that the exhaust gas organic for both tests was primarily aliphatic hydrocarbons, with some carboxylic acids, phenols, and low-molecular-weight fused-ring aromatics (e.g., naphthalene and alkyl naphthalenes).

Health effects bioassay tests were performed on the organic sorbent (XAD-2) module extract from the SASS trains for both the baseline and the low-$NO_x$ tests. The bioassay tests performed were the Ames mutagenicity and the CHO cytotoxicity assay. The results of these assays are summarized in Table 3 for the exhaust gas sample (organic sorbent module extract from the SASS train) for both the baseline and low-$NO_x$ tests. The results suggest that the exhaust gas under both baseline and low-$NO_x$ operation is of moderate to high toxicity and mutagenicity. This is a typical bioassay response for combustion source XAD-2 extract.

**Table 3.** *Bioassay Analysis Results*

| Sample | Test | Bioassay Analysis: CHO[a] | Bioassay Analysis: Ames[b] |
|---|---|---|---|
| XAD-2 Extract | Baseline | H/M | H |
| XAD-2 Extract | Low-$NO_x$ | H/M | M |

[a]H = high toxicity; M = moderate toxicity.
[b]H = high mutagenicity;
M = moderate mutagenicity.



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*C. Castaldini is with Acurex Corp., Mountain View, CA 94039.*
***Robert E. Hall** is the EPA Project Officer (see below).*
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*The EPA Project Officer can be contacted at:*
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# Project Summary

4.2

# Environmental Assessment of NOx Control on a Compression-Ignition, Large-Bore, Reciprocating Internal-Combustion Engine

C. Castaldini

**The report gives emission results from field testing of the exhaust gas from a large-bore, compression-ignition reciprocating engine burning diesel fuel. An objective of the tests was to evaluate the operating efficiency of the engine with combustion modification NOx control to reduce emissions to below the proposed NOx new source performance standard (NSPS) of 600 ppm at 15 percent $O_2$ dry. Engine NOx emissions were reduced 31 percent (from 825 to 571 ppm) at 15 percent $O_2$ with 3.5° of fuel injection timing retard. This reduction was accompanied by a 1 percent loss in engine efficiency. CO emissions decreased slightly (from 119 to 90 ppm). Total unburned hydrocarbons remained relatively unchanged (25 ppm), as did particulate emissions (35 ng/J) and total organic emissions (55 ng/J). Volatile organics (boiling point < about 100° C) accounted for the largest fraction of the total organic. Naphthalene, fluoroanthene, phenanthrene/anthracene, and pyrene were the only organic priority pollutants detected in both tests at levels below 70 micrograms/dscm.**

*This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in two separate volumes of the same title (see Project Report ordering information at back).*

## Introduction

This report describes emission results obtained from field testing of the exhaust gas from a large-bore, dual-fuel, compression-ignition, reciprocating internal-combustion (IC) engine burning distillate oil (diesel fuel). Objectives of the tests were to measure exhaust gas emissions and to evaluate the operating efficiency of the engine under baseline or normal operating conditions and with combustion modification NOx control to reduce emissions to below the proposed NOx New Source Performance Standard (NSPS) of 600 ppm at 15 percent $O_2$. Emission measurements included continuous monitoring of exhaust gas emissions; source assessment sampling system (SASS) sampling of the exhaust gas with subsequent laboratory analysis of samples to give total exhaust gas organics in two boiling point ranges, compound category information within these ranges, specific quantitation of the semivolatile organic priority pollutants, and exhaust gas concentrations of 73 trace elements; Method 5 sampling for particulate; Method 8 sampling for $SO_2$ and $SO_3$; and grab sampling of fuel and engine lubricating oil for inorganic composition determinations.

Engine NOx emissions were reduced 31 percent (from 825 to 571 ppm) at 15 percent $O_2$ with the control approach tested (3.5° of fuel injection timing retard). This reduction was accompanied by a 1 percent loss in engine efficiency (from 36.3 to 35.3 percent). CO emissions decreased slightly (from 119 to 90 ppm) at 15 percent $O_2$ under controlled operation. Total unburned hydrocarbon emissions remained relatively unchanged (at about 25 ppm, as propane) at 15 percent $O_2$, as did particulate emissions at about 35 ng/J heat input. Total organic emissions also remained relatively unchanged at about 55 ng/J. Volatile organics (boiling point less than about 100°C) accounted for the largest fraction of the total organic.

Of the 58 semivolatile organic priority pollutants analyzed, only naphthalene, fluoroanthene, phenanthrene/anthracene, and pyrene were detected in the uncontrolled engine exhaust at levels of 7 to 70 μg/dscm. Levels of these in the controlled engine exhaust were lower, being less than 1 to 50 μg/dscm.

## Summary and Conclusions

### *Test Engine*

The test engine was a turbocharged 1,565 kW (2,100-Bhp), two-stroke, opposed-piston, compression-ignition Model 38TDD8-1/8 engine manufactured by the Fairbanks Morse Engine Division of Colt Industries. Figure 1, a schematic of the engine, shows the turboblower arrangement of the inlet combustion air and the opposed-piston design. The combustion air is drawn into the turbocharger where it is compressed and discharged through an air cooler to the positive-displacement lobe-type blower. The blower, driven by the upper engine crankshaft, discharges the air directly to the cylinders through the engine intake manifold. The air/fuel mixture is compressed between the two pistons which work vertically toward each other in each cylinder. The upper and lower pistons drive separate crankshafts interconnected by a vertical drive. Hot exhaust gas leading from the lower cylinder ports drives the turbine of the turbocharger assembly. The fuel is ignited by the heat of compression.

### *Engine Operation and Test Arrangements*

The test program called for the analysis of exhaust gas samples collected (1) during uncontrolled or baseline operation, and (2) with fuel injection retard to lower NOx emissions to or below the level of the proposed NSPS. Table 1 summarizes the engine specifications, operating parameters, and atmospheric conditions during both tests.

For the baseline test, fuel injection timing was set at the normal setting for this engine, 16° before minimum volume (RMV). Combustion modification NOx control consisted of retarding the fuel injection timing from 16 to 10.5° BMV. The effect of 5.5° retard on the operation of the engine was a loss in efficiency of about 1.0 percent. This efficiency loss is clearly identifiable by the increase in fuel flow required to maintain rated power output. The air flow was also increased during the low-NOx tests as indicated by the increase in blower discharge pressure. However, the fuel/air ratio during the low-NOx test decreased about 8 percent from the baseline level. Blower discharge and engine exhaust gas temperatures remained nearly constant while there was a small reduction in temperature at the turbine outlet of the turbocharger.

## *Emission Measurements and Results*

The sampling and analysis procedures used in this test program conformed to a modified EPA level 1 protocol. Except for continuous monitoring to exhaust gas emissions, all exhaust gases were measured at the exit of the engine muffler into the uninsulated exhaust stack. Emission measurements included:

- Continuous monitoring for NOx, NO, CO, $CO_2$, $O_2$, and TUHC
- Source Assessment Sampling System (SASS) for trace elements and organic emissions
- EPA Method 5 for solid and condensible particulate mass emissions
- EPA Method 8 for $SO_2$ and $SO_3$ emissions
- Grab sample for onsite analysis of $C_1$ to $C_6$ hydrocarbons by gas chromatography (GC)
- Bosch smoke spot

In addition, samples of the engine lubricating oil and the diesel fuel oil were collected for analysis.

The analysis protocol included:

- Analyzing the fuel/lube oil, and SASS train samples for 73 trace elements using spark source mass spectrometry (SSMS), supplement-

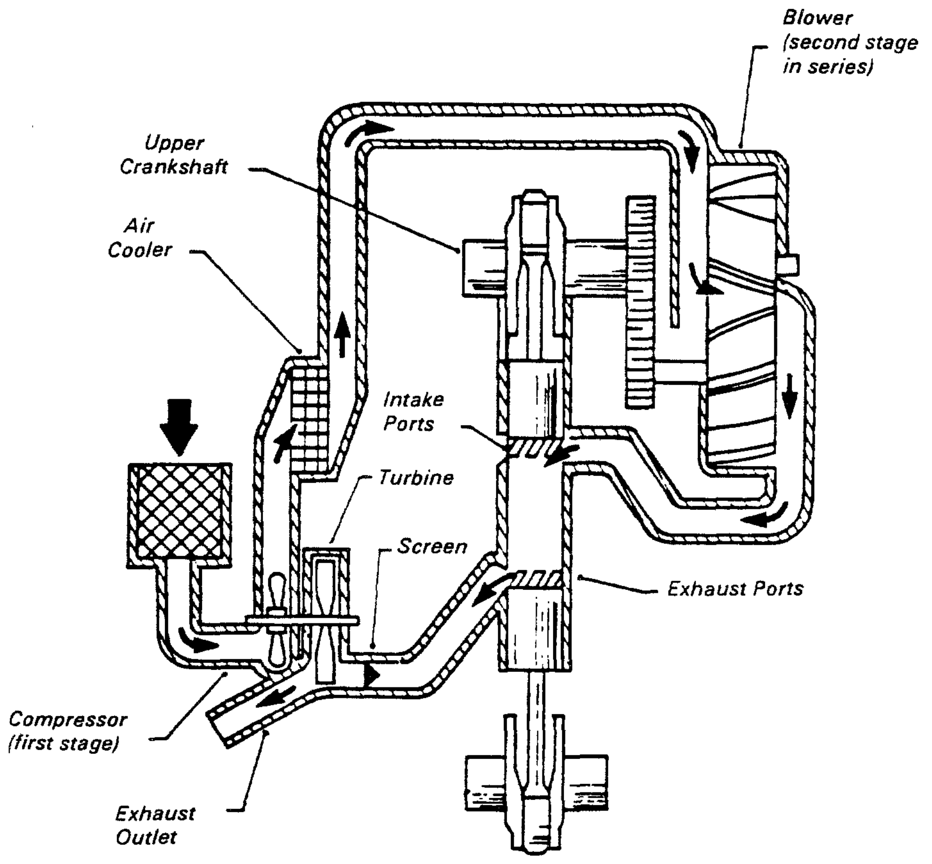


*Figure 1. Schematic of turboblower arrangement (courtesy of Fairbanks Morse Division of Colt Industries).*

ed by atomic absorption spectrometry (AAS)

- Analyzing SASS train samples for total organic content in two boiling point ranges: 100 to 300°C by total chromatographable organics (TCO) analysis and >300°C by gravimetry (GRAV)
- Analyzing the SASS train samples for 58 semivolatile organic species including many POM compounds
- Performing infrared (IR) spectrometry analysis of organic sample extracts
- Performing liquid chromatography (LC) separation of selected sample extracts with subsequent TCO, GRAV, and IR analysis of LC fractions
- Performing direct insertion probe and batch inlet low resolution mass spectrometry (LRMS) of selected sample extracts

Bioassay tests were also performed on the SASS organic sorbent module extract to estimate this sample's potential toxicity and mutagenicity.

Table 2 summarizes exhaust gas emissions measured in the test program. Emissions are presented as ng/J heat input and as mg/dscm of exhaust.

As noted in Table 2, NOx emissions were reduced with fuel injection retard to 1,040 ng/J from a baseline of 1,490 ng/J. CO emissions were also decreased slightly. TUHC, particulate, and total semivolatile organic emissions were relatively unchanged; nonvolatile organic emissions increased with low-NOx operation.

As a measure of the potential significance of the emissions levels for further monitoring evaluation, Table 2 also lists occupational exposure guidelines for most pollutants noted in the table. The guidelines listed are generally either time-weighted-average Threshold Limit Values (TLV) established by the American Conference of Governmental Industrial Hygienists, or the 8-hr time-weighted-averaged exposure limits established by the Occupational Safety and Health Administration. These are noted only to aid in ranking the emissions for evaluation. In this respect, pollutants emitted at levels several orders of magnitude higher than their guideline might warrant further consideration, while species emitted at levels significantly lower than their guideline might be considered of lesser concern. Only elements emitted at levels exceeding 10 percent of their guideline are noted in Table 2.

Table 2 shows that several trace elements were emitted at levels up to eight times their respective guidelines. For comparison, emissions of the gaseous pollutants CO, $SO_2$, and $SO_3$ were at levels ranging from 2 to 20 times their guidelines; NOx emissions were at levels over 300 times its guideline. These comparisons suggest that the NOx control achieved may be the most significant change.

Analyses of SASS train samples for POM and other organic compounds (the semivolatile organic priority pollutants species) were performed. Only naphthalene, fluoroanthene, phenanthrene/anthracene, and pyrene were detected in the baseline test exhaust gas at levels of 7 to 70 μg/dscm. Levels of these compounds in the low-NOx test exhaust gas were lower, from less than 1 to 50 μg/dscm.

SASS train organic extract samples were subjected to LC fractionation, with TCO, GRAV, IR, and LRMS analysis of LC fractions, in attempts to elucidate the chemical character of the exhaust gas organic material. These analyses suggested that the exhaust gas organic for both tests was primarily aliphatic hydrocarbons with some esters, carboxylic acids, phenols, mercaptans,

**Table 1.** *Compression Ignition Engine Design and Operating Parameters*

| Engine Design Parameters | Specifications | |
|---|---|---|
| Model designation | 38TDD8-1/8 | |
| Engine configuration | 2-stroke, opposed-piston | |
| Bore/stroke, m (in.) | 0.206/0.254 (8-1/8/10) x 2 | |
| Number of cylinders | 6 | |
| Displacement/cylinder, $m^3$ ($in.^3$) | 0.017 (1.037) | |
| Compression ratio | 11:1 | |
| BMEP, MPa (psia) | 1.01 (148.5) | |
| kW/cylinder (Bhp/cylinder) rpm | 261 (350) at 900 rpm | |
| Injection timing | 16° before minimum volume (BMV) | |
| Lubricating oil | Mobil 446 | |
| Lubricating oil consumption, ml/s (gph) | 0.37 (0.35) | |
| Fuel oil | No. 2 | |
| Hours since last overhaul | 30 | |
| **Engine Operating Parameters** | **Baseline** | **Low-NOx** |
| RPM (percent rating) | 900 (100%) | 900 (100%) |
| $kW_t$ (Bhp) (percent rating) | 1566 (2100) (100%) | 1567 (2101) (100%) |
| Generator output, $kW_e$ (percent rating) | 1503 (9.8%) | 1505 (99.8%) |
| Fuel flow, g/s (lb/hr) | 97.7 (775) | 101 (798) |
| BSFC, g/kW-hr (lb/Bhp-hr) | 225 (0.37) | 231 (0.38) |
| Fuel rate, $kW_t$ in/$kW_t$ out (Btu/Bhp-hr) | 2.75 (7009)[a] | 2.84 (7218)[a] |
| Injection timing | 16.0° BMV | 10.5° BMV |
| Cylinder firing pressure, MPa (psig) | 9.02-9.23 (1320-1350) | 8.20-8.34 (1200-1220) |
| Compressor inlet air temp., K (°F) | 305 (89) | 291 (65) |
| Compressor outlet air temp., K (°F) | 417 (292) | 414 (286) |
| Blower suction temp., K (°F) | 324 (124) | 327 (130) |
| Blower discharge temp., K (°F) | 338 (149) | 340 (153) |
| Blower discharge pressure, kPa (psig) | 150 (22.0) | 176 (25.7) |
| Air flow, kg/s (lb/min) | 4.05 (535) | 4.52 (598) |
| Fuel/air ratio | 0.02414 | 0.02223 |
| Combined cylinder exhaust temp., K (°F) | 757 (903) | 754 (898) |
| Turbine exhaust temp., K (°F) | 636 (686) | 625 (665) |
| Engine efficiency, percent | 36.3 | 35.3 |
| **Average Ambient Atmospheric Condition** | | |
| Ambient temperature—dry bulb, K (°F) | 304 (88) | 290 (63) |
| Barometric pressure, kPa (in. Hg) | 97.3 (28.82) | 98.2 (29.07) |
| Relative humidity, percent | 37 | 45 |

[a]Heat input accounts for the heating value of lube oil burned by the engine.

*Table 2. Summary of Exhaust Gas Emissions*[a]

| Compound | Baseline Test (ng/J Heat Input) | Baseline Test (mg/dcsm) | Low-$NO_x$ (ng/J Heat Input) | Low-$NO_x$ (mg/dscm) | Occupational Exposure Guideline (µg/dscm)[b] |
|---|---|---|---|---|---|
| *Criteria Pollutants and Other Vapor Species* | | | | | |
| $NO_x$ (as $NO_2$) | 1,490 | 1,940 | 1,040 | 1,230 | 6.0 |
| CO | 130 | 170 | 98 | 117 | 55 |
| TUHC (as $C_3H_8$) | 45 | 59 | 42 | 50 | —[c] |
| $SO_2$ | 44 | 57 | 95 | 113 | 5.0 |
| $SO_3$ | 11 | 14 | 19 | 23 | 1.0 |
| Solid particulate | 29.5 | 38.4 | 36.6 | 43.7 | 10.0[d] |
| Condensible particulate | 3.3 | 4.5 | —[e] | — | |
| Total semivolatile organics ($C_7$-$C_{16}$) | 1.1 | 1.5 | 1.2 | 1.4 | —[c] |
| Total nonvolatile organics (>$C_{16}$) | 3.5 | 4.6 | 12.2 | 14.5 | —[c] |
| *Trace Elements* | | | | | |
| Phosphorus, P | >0.61 | >0.79 | 0.045 | 0.054 | 0.10 |
| Copper, Cu | 0.062 | 0.081 | 0.34 | 0.40 | 0.10[f] |
| Iron, Fe | 0.020 | 0.026 | 0.92 | 1.1 | 1.0 |
| Silver, Ag | 0.0085 | 0.011 | <0.0017 | <0.0020 | 0.010 |
| Potassium, K | >1.1 | >1.4 | >0.60 | >0.72 | 2.09 |
| Sodium, Na | >0.63 | >0.82 | >0.55 | >0.65 | 2.09 |
| Calcium, Ca | >0.54 | >0.70 | — | — | 2.0 |
| Aluminum, Al | 0.53 | 0.69 | 0.010 | 0.012 | 2.0 |
| Zinc, Zn | 0.065 | 0.085 | 0.23 | 0.27 | 1.0 |
| Chromium, Cr | 0.0020 | 0.0026 | 0.010 | 0.012 | 0.050 |
| Lead, Pb | 0.0007 | 0.0009 | 0.0072 | 0.00087 | 0.050[f] |
| Nickel, Ni | 0.012 | 0.015 | 0.0034 | 0.0041 | 0.10 |
| Selenium, Se | 0.020 | 0.026 | 0.023 | 0.027 | 0.20 |

[a]Exhaust $O_2$ and $CO_2$ levels were 13.7 and 5.3 percent, respectively, for the baseline test and 14.3 and 5.0 percent, respectively, for the low-$NO_x$ test.
[b]Time-weighted-average TLV unless noted.
[c]No occupational exposure guideline applicable.
[d]For nuisance particulate.
[e]Sample lost.
[f]8-Hr time-weight-average OSHA exposure limit.

and low-molecular-weight fused-ring aromatics (e.g. naphthalene and alkyl naphthalenes).

Bioassay tests were performed on the organic sorbent module extract from the SASS trains for both tests. The health effects bioassay tests performed were the Ames mutagenicity assay, and the CHO cytotoxicity assay. The results of these assays are summarized in Table 3. The results suggest that the exhaust gas under both baseline and low-NOx operation is of moderate to high toxicity and moderate mutagenicity. This is a typical bioassay response for combustion source SASS train XAD-2 extract.

*Table 3. Bioassay Analysis Results*

| Sample | Test | Bioassay Analysis CHO[a] | Bioassay Analysis Ames[b] |
|---|---|---|---|
| XAD-2 Extract | Baseline | H | M |
| XAD-2 Extract | Low-$NO_x$ | H/M | M |

[a]H = High toxicity, M = Moderate toxicity.
[b]M = Moderate mutagenicity.



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